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Abstract

Researchers at NASA Langley Research Center have extensive experience using active structural acoustic control (ASAC) for aircraft interior noise reduction. One aspect of ASAC involves the selection of optimum locations for microphone sensors and force actuators. This paper explains the importance of sensor/actuator selection, reviews optimization techniques, and summarizes experimental and numerical results.

Three combinatorial optimization problems are described. Two involve the determination of the number and position of piezoelectric actuators, and the other involves the determination of the number and location of the sensors. For each case, a solution method is suggested, and typical results are examined. The first case, a simplified problem with simulated data, is used to illustrate the method. The second and third cases are more representative of the potential of the method and use measured data. The three case studies and laboratory test results establish the usefulness of the numerical methods.

Introduction

Active acoustic control, or the use of one acoustic source (or secondary source) to cancel another (or primary source), has a long history. In a recent survey paper, Fuller and Von Flotow[1] describe practical demonstrations of the technique as early as 1953 and a U.S. patent as early as 1936. In addition, these authors describe several commercially successful active noise and vibration control systems in use today. Their paper is highly recommended to any reader who desires a complete discussion of active acoustic control and its practical uses.

The scope of the present paper is limited to active structural acoustic control (ASAC), with a focus on aircraft interior noise control research conducted at NASA Langley Research Center. The most obvious difference between the ASAC system and early acoustic control systems is that ASAC uses structural actuators like shakers or piezoelectric (PZT) patches attached to the aircraft fuselage rather than acoustic actuators like loudspeakers inside the fuselage. The ASAC concept is attractive because the structural actuators are more effective by weight and consume less interior volume than competing active or passive noise control options.[2]

One area of ASAC research is the determination of optimal locations for actuators and sensors. Early theoretical investigations[3–5] established the importance of actuator and sensor architecture and suggested

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optimization strategies and goals. For example, Silcox et al.[3] introduce a mathematical model for ASAC and demonstrate that for fixed actuator and sensor locations the force inputs that yield minimum interior noise are easy to calculate. Ruckman and Fuller[4] suggest that the best actuator locations can be found by selecting subsets of actuators from a large set of candidates. They further suggest statistical measures that test whether seemingly good actuator sets will perform well in spite of measurement noise and numerical errors. In reference 5, Padula and Kincaid solve the ASAC actuator subset selection problem by using a combinatorial search method that was originally applied to spacecraft optimization problems. References 6 and 7 supply details in regard to the search method and suggest several modifications that improve its usefulness and efficiency.

In their survey paper, Fuller and Von Flotow[1] describe the actuator location problem from a practical standpoint. They note that researchers recommend a modal method, such that actuators are placed to excite a selected structural mode and sensors are placed to observe each important acoustic mode. Lyle and Silcox[2] tested this modal method on a simulated aircraft fuselage with mixed results. They demonstrated impressive global interior noise reduction at a frequency at which both the primary and secondary sources excited the same dominant acoustic mode. However, at a second frequency, the same actuator and sensor configuration should have been effective, yet when tested a global increase in interior noise was noted. Lyle and Silcox explain that in the second case several acoustic modes were important and, although the controller successfully reduced the dominant mode, several other modes were amplified (i.e., control spillover was observed). Further, the authors demonstrated that an alternate set of actuators and sensors greatly reduced the spillover effect.

This report reviews combinatorial optimization techniques for actuator and sensor location problems. The report extends the material in reference 5 in several ways. First, the optimization techniques are demonstrated by application to test articles. Next, the optimized sensor and actuator architectures are compared with those derived by modal methods. Finally, the optimization methods are extended to cases in which several frequencies are controlled simultaneously and in which actuator excitation voltages cannot exceed transducer saturation limits.

Three combinatorial optimization problems are described in this report. All involve determination of the best positions for ASAC sensors and actuators. For each case, a solution method is suggested, and typical results are examined. The first case is a simplified problem with simulated data that is used to illustrate the method. The second case applies the technique to the laboratory model used by Lyle and Silcox and compares the automated procedure with the modal method. The final case is more representative of the potential of the method and shows how the method can be extended to include a large number of actuators that must reduce noise at multiple frequencies and that have realistic force limits.

Optimization Overview

In this section, a combinatorial optimization method for selecting actuator (or sensor) locations is described. All three test cases in this paper use some variation of this generalized algorithm.

Given a set of N_a actuator locations, the goal of an optimization run is to identify a subset of N_c locations that provides the best performance (e.g., reduces interior noise). Several combinatorial optimization methods, such as simulated annealing, genetic algorithms, and tabu search, are available. Tabu search was selected for use in the present study, based on previous experience.[5]

To apply a tabu search algorithm one must define a state space, a method for moving from state to state, a neighborhood for each state, and a cost function to minimize. For the actuator selection problem, the set of all possible subsets of size N_c chosen from N_a actuators is the state space. To bound the problem, the subset size N_c is constant for each search. An initial state can be prescribed by the user or can be generated randomly. At any given state, the subset N_c, of actuators that represent that state are flagged as "on;" the remaining actuators are flagged as "off." A move changes the state by turning one actuator off and one on. A neighborhood is the set of all states that are one move away from the current state. Finally, the cost function is based on the noise reduction estimate for the subset of actuators that are turned on.

Each iteration of the tabu search algorithm involves evaluating the cost function for each subset of actuators in the neighborhood of the current state. The move that improves the cost function the most is accepted. If no improving move is identified, then the move that degrades the cost function the least is accepted. The algorithm continues for a predetermined number of iterations. Cycling is avoided by maintaining a list (called the tabu list) of all accepted moves. The algorithm is prohibited from reversing any move on the tabu list. An exception can be made if the move is old or if the move produces a state that is clearly better than any previous state. The algorithm terminates after reporting the best state that was encountered during the entire optimization procedure.

Note that each iteration of tabu search requires $N_c*(N_a - N_c)$ evaluations of the cost function. For example, in the first test case, tabu search is used to select 16 actuator locations from a possible 102. This scenario requires 16*86 = 1376 evaluations per iteration. Typical searches require at least 15 iterations, or approximately 2×10^5 evaluations. This number of evaluations is small in comparison with the total number of possible actuator combinations ($\sim 2 \times 10^{18}$) but can be significant if the cost function is computationally expensive. Selection of the least computationally expensive cost function that maintains the relative ranking of the actuator sets in the search space is desirable. The cost function is not required to be smooth or continuous or quantitatively accurate. The only requirement is that the cost function can identify the better of two actuator sets.

Simulated ASAC

In this section, tabu search is applied to a simplified model of the ASAC problem. This simulation serves several purposes. First, the simulation illustrates the method and indicates the potential for reducing aircraft interior noise. Secondly, the relationship between the shell vibration level and the interior noise level is explored.

Problem Statement

Assume that an aircraft fuselage is represented as a cylinder with rigid end caps (fig. 1) and that a propeller is represented as a point monopole with a frequency equal to some multiple of the blade passage frequency. Piezoelectric actuators bonded to the fuselage skin are represented as line force distributions in the x and θ directions. With this simplified model, the point monopole produces predictable pressure waves that are exterior to the cylinder. These periodic pressure changes cause predictable structural vibrations in the cylinder wall and predictable noise levels in the interior space. The interior noise level at any discrete microphone location can be dramatically reduced by using the PZT actuators to modify the vibration of the cylinder. For a given set of microphones and a given set of actuator locations, the control forces that minimize the acoustic response are known.[3] However, methods for choosing good locations for the microphones and the actuators are needed.[8]

In accordance with the notation used in reference 9, the ASAC optimization problem is to minimize the sum of squared pressures at a set of N_p interior microphones:

$$E = \sum_{m=1}^{Np} \Lambda_m \Lambda_m^* \tag{1}$$

where * indicates the complex conjugate. The response at microphone m is given as

$$\Lambda_m = \sum_{k=1}^{Nc} H_{mk} c_k + p_m \tag{2}$$

where p_m is the response with no active control and H_{mk} is a complex-valued transfer matrix that represents the response at microphone m that results from one unit control force ($|c_k| = 1$) at actuator k. The values in the transfer matrix can be collected experimentally (ref. 2), or they can be simulated (ref. 3).

The cost function can be written either as in equation (1) or on a decibel scale to compare the interior pressure norms with and without ASAC:

$$\text{Level} = 10 \log\left(\sum_{m=1}^{Np} \Lambda_m \Lambda_m^* \Big/ \sum_{m=1}^{Np} p_m p_m^* \right) \tag{3}$$

A negative level represents a decrease in sound pressure level caused by the action of PZT actuators.

For a fixed set of N_c actuators, the forces c_k that minimize either equation (1) or equation (3) can be determined by solving a complex least-squares problem.[3] Unfortunately, the solution vector may contain values of c_k that exceed the maximum allowable control force. Also, for some sets of actuators the solution vector decreases the interior noise level but increases the shell vibration level. (Note that an equation similar to equation (3) exists that compares the vibration norms with and without

ASAC. A positive vibration level indicates an increase in shell vibration as a result of the action of PZT actuators.) Effective noise control strategies can either reduce the vibration of the cylinder or magnify the vibration of the cylinder by shifting vibrational energy to shell modes that do not couple efficiently with acoustic modes.[8] This insight is important because aircraft manufacturers may reject a noise control method that increases vibration and, in turn, increases the potential for fatigue failure of the airframe.

One approach to this problem of minimizing noise and vibration is to assume that the forces c_k are variable but their locations are fixed. For example, reference 9 uses a multiobjective optimization formulation to trade off noise reduction and vibration reduction while imposing force constraints. This formulation can be successful but is highly sensitive to the weights placed on each objective.

An alternate way to pose the problem is to make the control forces dependent variables and choose the number and locations of the actuators. Given a large number N_a of possible locations and a transfer matrix $\mathbf{H}^a$ that includes the response for each possible actuator, the alternate procedure uses tabu search to converge to the best $N_c << N_a$ of these locations. As each proposed subset is considered, the matrix $\mathbf{H}$ is assembled by extracting the appropriate columns of $\mathbf{H}^a$. Then, the vector of control forces that minimizes E (eq. (1)) is calculated, and the corresponding noise level (eq. (3)) is used to determine the cost of the proposed move.

Results

The results from the simulated studies are encouraging. For varying numbers of possible locations, subset sizes, source frequencies, and sets of interior microphones, the same trends are observed. Namely, the subset of actuators selected by tabu search to reduce interior noise tends to reduce cylinder vibration as well. Figure 2 shows typical results. In the figure, noise and vibration levels are plotted versus the tabu search iteration number. The 16 best locations are chosen from a set of 102 possible locations. Notice that the initial set of 16 actuators reduces the noise by 13 dB but increases the cylinder vibration by 4 dB. However, after 15 iterations, both noise and vibration levels are reduced dramatically. Fifteen additional iterations produce no significant improvement. By adjusting the number of actuators up or down from 16, the noise-reduction goals can be satisfied without an increase in vibration and without exceeding the force capacity of the PZT actuators.

The best locations for PZT actuators are not intuitively obvious. For example, figure 3 shows the grid of 102 possible locations distributed in 6 rings of 17 locations each. Each actuator location is specified by the (x, θ, $r = a$) position of its center. (Recall fig. 1.) The acoustic monopole is located at ($x = L/2$, $\theta = 0$, $r = 1.2a$), where L is the cylinder length and a is the cylinder radius. (The dimensions of the cylinder are typical of commuter aircraft configurations, and the frequency of the source simulates harmonics of typical turboprop blade passage frequencies.) The shaded rectangles indicate the 16 best actuator locations. Figure 3(a) shows the best locations for controlling interior noise caused by an acoustic monopole with a frequency of 200 Hz. Figure 3(b) indicates the change in the best locations for an acoustic monopole with a frequency of 275 Hz. Notice the symmetric pattern in figure 3(a) that corresponds to a case in which the acoustic monopole excites one dominant interior cavity mode. Notice the greater complexity of the pattern in figure 3(b). Here, several cavity modes of similar importance are excited by the monopole with a frequency of 275 Hz.

Experimental ASAC Studies

The results in figures 2 and 3 are idealized and are based on simulated transfer matrices. However, these results indicate the importance of actuator location in active structural acoustic control. Experimental tests are a necessary next step. In these tests, the transfer matrix is constructed by using measured data, and the effectiveness of selected locations can be verified experimentally. This section describes two such tests. The discussion for each test includes the facility that was used to acquire the data, the tabu search problem that was used to pick the actuator or sensor locations, and typical results. More complete descriptions and discussion of results are available in the references.

Langley Composite Cylinder

The composite fuselage model is shown in figure 4. The cylinder is 3.6 m long and 1.68 m in diameter. The outer shell is graphite epoxy, which is stiffened by composite stringers and ring frames. The interior has a plywood floor and inner trim panels that are attached to the ring frame. The primary source is a 100-W electrodynamic loudspeaker that is mounted 0.3 m from the exterior sidewall. The secondary source is a subset of the eight piezoelectric actuators bonded to the interior trim panels. (See fig. 5.)

Data are collected by six boom-mounted microphones. The boom can translate and rotate to collect sound pressure levels at 11 azimuthal ($-108^o < \theta < +108^o$), 7 axial ($0.36 \text{ m} < x < 3.23 \text{ m}$), and 6 radial positions ($0.13 \text{ m} < r < 0.73 \text{ m}$), for a total of 462 data points within the cylinder volume. Two of the cross sections surveyed by the boom microphones are indicated in figure 5.

The interior noise data are collected for three different frequencies: 210, 230, and 275 Hz. For each frequency, the data are collected for the primary source alone and then for the secondary source alone by using a single unit input separately at each of the eight actuators. In this way, 462 x 1 elements of the primary vector and 462 x 8 elements of the transfer matrix are assembled for each frequency. The three frequencies are well chosen. The first (i.e., 210 Hz) represents a case in which a single dominant acoustic mode is easily controlled with a single structural mode. The other two frequencies represent cases in which no particular acoustic or structural mode is dominant or in which several modes are important.

Single Frequency Optimization Method

The goal of the optimization is to pick the four best actuators and the eight best sensors for use in active noise control. Tabu search may be used to select four out of eight actuators; however, because only 70 possible combinations exist, each combination is evaluated by using equations (1)–(3). On the other hand, approximately 5×10^{16} combinations of 8 sensors can be selected from 462 candidates. Therefore, after the four best actuators have been identified, tabu search is used to select the best microphones to use with those actuators. Again, equations (1)–(3) are used to compare the candidates. However, in this instance, the optimal control forces c_k are calculated with the 8 x 4 matrix $\mathbf{H}$, and the noise reduction is calculated using the 462 x 4 matrix $\mathbf{H}^a$. In other words, the goal is to reduce noise at all microphones, but only eight microphones are used by the controller.

Random selections of actuator and sensor locations were evaluated prior to the tabu search optimization. Figure 6 indicates the results of those random trials for the three frequencies of interest. Of the 70 possible actuator sets, only the best and worst appear on this graph. For each set of 4 actuators, 1000 different sets of 8 sensors were selected at random. The noise reduction potentials for those 2000 sensor and actuator architectures are collected as a histogram. Figure 6(a) contains the histogram associated with the source at 210 Hz. Note that approximately 50 of the randomly selected architectures are predicted to reduce noise by at least 5 dB and approximately 50 are predicted to **increase** noise by at least 3 dB. The histograms for 230 and 275 Hz have a similar range of noise reduction potential. However, notice that in figures 6(b) and 6(c) the difference between the sets of best and worst actuators is more pronounced. These random trials emphasize the importance of actuator and sensor selection.

The goal of the composite cylinder laboratory tests is to reduce noise at all 462 microphone locations by using a linear control law with feedback from 8 of the 462 microphones.[10] Clearly, tabu search must identify microphones that are able to observe all important acoustic modes. Moreover, some linear combination of the selected actuator responses must approximately cancel out the primary response.

The initial tabu search results did not meet our expectations. The optimization procedure did identify an architecture with greater noise reduction potential than any of those found by random trials. However, inspection of the contour maps of the interior noise indicates that many of the selected sensors are in low noise areas where the change in noise as a result of the control system is small. These poor subsets are characterized[11,12] by a high statistical variance measure $v(c_k)$ for one or more of the actuator forces:

$$v(c_k) = \text{diag}_k \left[\sigma^2 \left(\mathbf{H}^* \mathbf{H}\right)^{-1}\right] \tag{4}$$

where diag_k denotes the kth diagonal, σ^2 is an estimate of the microphone measurement inaccuracy, and $\mathbf{H}^*$ is the Hermitian conjugate of $\mathbf{H}$. A large absolute value for any $v(c_k)$ or a large sum of variances suggests that this architecture could be sensitive to measurement noise, has insufficient sensors to characterize the response field, or includes actuators that are decoupled (i.e., the actuators excite a different set of acoustic modes than those found in the response). Reference 12 has an excellent discussion of the physical interpretation of the variance measure.

To select better actuator/sensor combinations, the tabu search cost function was modified to include a variance measure in addition to a noise reduction measure. Both absolute value and sum of variances were tried with equal success.[7] The final version of the optimization procedure is summarized as follows:

1. Select 4 actuators; evaluate all combinations
2. Form 462 x 4 matrix $\mathbf{H}^a$
3. Choose 8 sensors at random
4. Form $\mathbf{H}$ matrix by collecting 8 rows from $\mathbf{H}^a$
5. Predict control forces c_k that minimize eq. (1)
6. Predict variance using $\mathbf{H}$
7. Predict noise reduction using c_k and $\mathbf{H}^a$
8. Select new sensors using tabu search
9. Repeat from step 4

Composite Cylinder Results

The composite cylinder model was used to test the selected actuator and sensor locations. The four best and four worst actuators were tested. For each actuator set, the eight best sensors were determined by tabu search. These test results are compared with previous test results in which the actuators and sensors were selected by using modal methods.

Test results are reported in reference 10 and summarized here. As expected, the control forces predicted in step 5 of the optimization procedure and the noise reduction predicted in step 7 do not match the observed control forces or noise reduction. Possible explanations for the differences include premature convergence of the optimal control algorithm and errors in the measured transfer functions. However, the trends are well predicted. For example, the noise reductions observed for the case in which the frequency was equal to 210 Hz are not sensitive to actuator set selection. (Recall fig. 6(a).) This case has one dominant acoustic mode. On the other hand, the noise reduction observed for the cases with frequencies of 230 Hz and 275 Hz shows a strong dependence on actuator location. The results in table 1 are typical.

Table 1. Optimization Results at 275 Hz

Selection criteria	Predicted reduction	Measured reduction
Best 4 actuators and best sensors	–5.7 dB	–3.9 dB
Worst 4 actuators and best sensors	–0.5 dB	–0.4 dB
Modal method	N/A	–2.7 dB

Notice that the observed noise reduction is less than predicted. However, the four best actuators provide 3.5 dB more noise reduction than the four worst and, in addition, perform better than those selected by modal methods. This finding suggests that the tabu search procedure is particularly effective in those cases in which tradeoffs between several important acoustic modes must be considered.

Fuselage Acoustic Research Facility

Data taken at the McDonnell Douglas Fuselage Acoustic Research Facility (FARF) serve as a basis for this study.[13] (See figure 7.) The FARF is a large anechoic room that contains the rear section of a DC-9 aircraft minus the engines and the tail. The interior is complete with seats and trim panels. An isolated volume that contains three rows of seats was formed by using two acoustically treated barriers. The data were originally acquired to support broadband noise control experiments. A large external loudspeaker was used as the primary source. Eighteen microphones were located at head height, one for each seat (15) and 3 in the aisle. A total of 64 actuators were bonded to the interior of the aircraft skin within the isolated volume on the bay areas formed by the ring frames and longerons.

Multiple Frequency Optimization Method

Solving for control forces with equation (2) produces a solution without regard to limitations that may exist on the force that the piezoelectric actuator is able to apply. The actuator force may be limited by many factors, for example, the design of the actuator, the manner in which it is mounted, and the actuator power supply. Recall that the tabu search process uses the control solution to compute the associated noise reduction. To obtain a realizable solution from the optimization process, the control solution must be bounded, or constrained. The control solution is given in terms of actuator voltage. To constrain the actuator force, an upper bound is placed on the voltage of the associated control signal.

In the previous section, the optimization method reduced noise at a single frequency. Here, the actuator locations that reduce noise at several different frequencies are sought. This procedure is accomplished by solving equation (2) once for each frequency and by modifying equation (3) to have double summations over frequency and sensors. The challenging feature of this method is that the force constraints are applied actuator by actuator. Thus, the sum of the forces that result from each frequency may not exceed a given limit. Several different methods for including these force constraints have been considered with varying degrees of success.[14]

FARF Results

The optimized locations of 14 actuators selected by tabu search are shown in figure 8. The numbered rectangles indicate the 64 candidate actuator locations and their positions relative to the windows shown in figure 7. The shaded rectangles indicate the selected actuators for both the constrained (fig. 8(a)) and unconstrained (fig. 8(b)) cases. The constrained set of actuators produced a 4.6 dB reduction in noise level using, at most, 2.25 Vrms of electrical excitation; the unconstrained set of actuators resulted in a reduction of 17.8 dB. The actuator array selected for the constrained case is quite different from the one selected for the unconstrained case. One hypothesis is that the unconstrained optimization is able to select actuators that have little or no effect at reasonable force levels but achieve greater noise reduction at the expense of much greater forces. Another possibility is that the unconstrained optimization seeks out ill-conditioned architectures that reduce noise dramatically at the 18 microphone locations but actually increase noise elsewhere. Fuller describes this second possibility in reference 12 and recommends statistical tests to diagnose the problem. The best solution would include further testing in the FARF; however, this additional testing has not been possible to date.

The ability of a particular actuator set to perform at force levels other than the constraint level for which it was optimized is an important consideration. Figure 9 plots the noise reduction for the two actuator sets shown in figure 8 (one set was optimized with force constraints and one was optimized without) over a range of force from 2.25 to 100 Vrms. The figure shows that the constrained actuator set has a greater potential for reducing noise at realistic levels (i.e., << 20 Vrms) than the unconstrained set.

Concluding Remarks

This paper summarizes several years of research on optimizing actuator and sensor locations for active structural acoustic control (ASAC). Clearly, optimized architectures are critical to the success of ASAC. For laboratory tests, with simplified acoustic sources and environments, the best locations possibly can be selected by inspection or modal methods. For small numbers of actuators and sensors, the evaluation of all possible combinations may even be practical. However, for complicated acoustic enclosures, such as an aircraft fuselage, and for reasonable numbers of candidate actuators and sensors, a combinatorial optimization method such as tabu search can improve the quality of the locations selected.

A tabu search method is presented that examines a tiny portion of the combinatorial design space yet identifies actuator locations that are better than those found by traditional modal methods. The method has been extended to select actuators that are appropriate for several different frequencies simultaneously and that include realistic limits on the force available for control. Laboratory tests that compare the noise reduction capabilities of optimized locations with those of locations selected by engineering judgment indicate the value of the tabu search procedure.

Actuator performance varies with applied force. Some actuator locations deliver good performance at low force levels and average performance at high forces. Other actuators with poor performance at low levels have average performance at high forces. For the purposes of selecting an optimized actuator set, the application of a reasonable force constraint is necessary. Precise duplication of the force (power) specification of the target system is not necessary. Constrained actuator sets perform well over a broad range of forces. Research has demonstrated that optimized but unconstrained actuator sets can have as members poorly performing actuators that require large amounts of force. This possibility underscores the need to constrain the forces used during optimization.

One weakness in the method is the need for accurate models of the closed loop performance of the control system. For now, the control system is modeled by using a linear transfer function. This transfer function is expensive to produce. The transfer function can be created experimentally, in which case the unit response must be measured for a large number of candidate actuator and sensor locations. On the other hand, the transfer function can be simulated, in which case a highly accurate model of the acoustic source and enclosure is required.

Two areas require additional research to improve upon the present actuator and sensor optimization process. The first involves generation of the transfer function. Measured data from a small number of actuators and sensors can potentially be enhanced to estimate the response at a larger number of candidate locations. The second area that requires additional research involves adaptive configuration optimization. An active structural acoustic control system could be built with more actuators and sensors than the control system can use simultaneously. An in-flight actuator and sensor optimization process could be used to reconfigure the control system if a device failure occurred or if unusual aircraft operating conditions reduced the effectiveness of the original actuator and sensor configuration.

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<u>Figures</u>

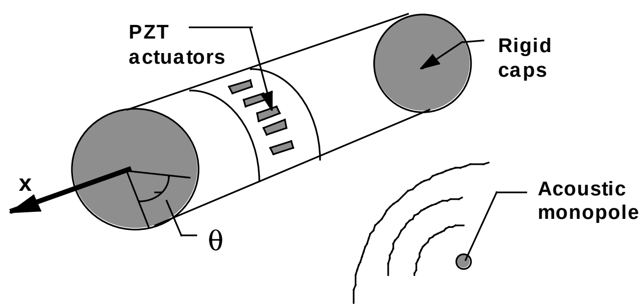


Figure 1. Schematic of simplified cylinder, point source, and actuator model.

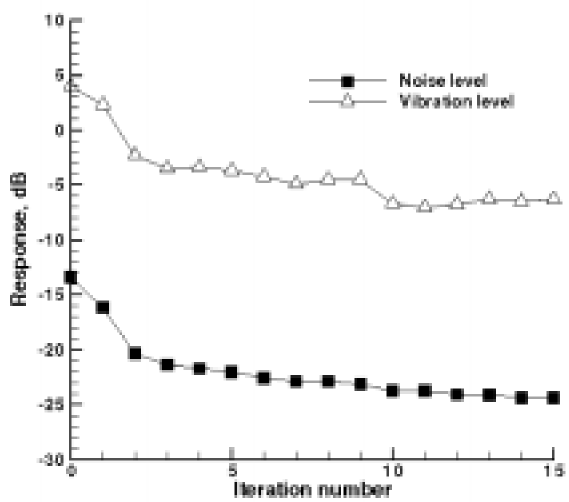
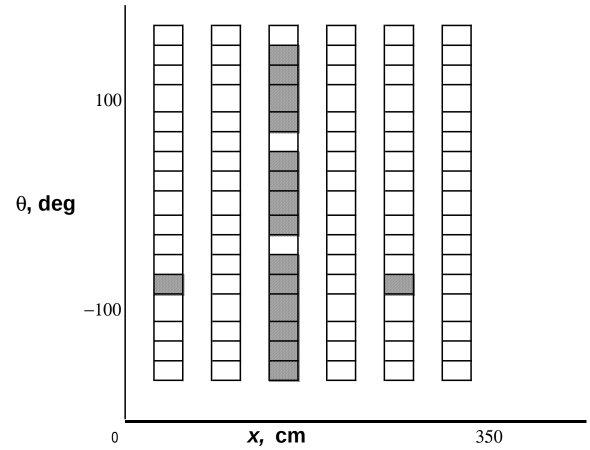
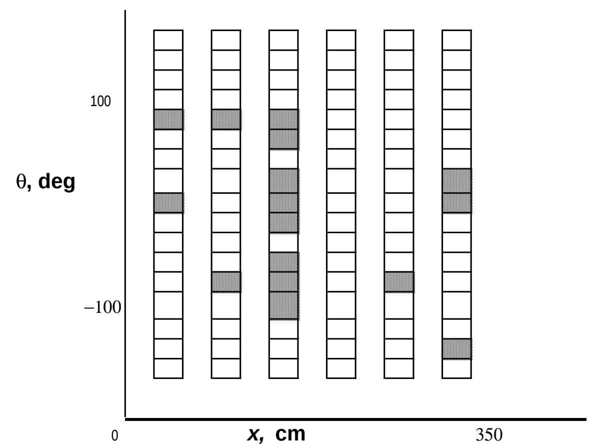


Figure 2. Typical tabu search history showing simultaneous reduction of noise and vibration.



(a) Frequency = 200 Hz.



(b) Frequency = 275 Hz.

Figure 3. Optimal (shaded) locations for 16 actuators on simplified cylinder model.

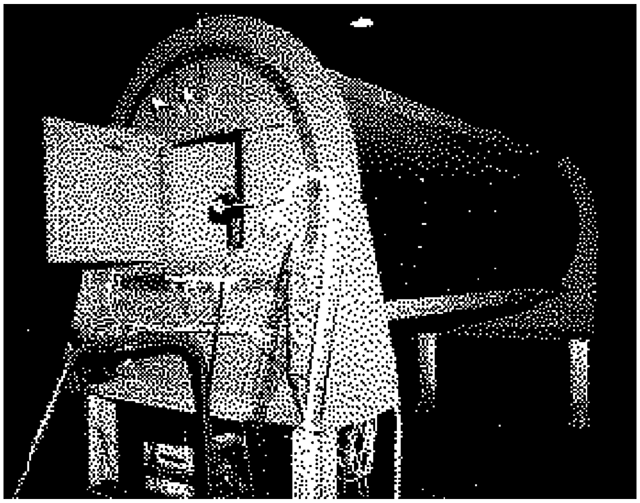


Figure 4. Composite cylinder at NASA Langley

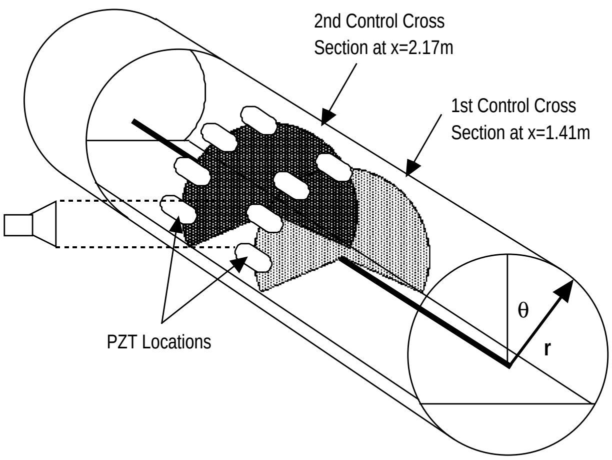
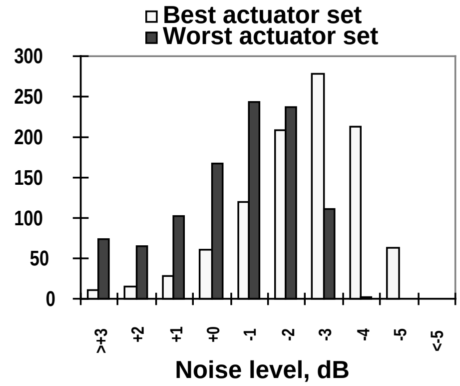
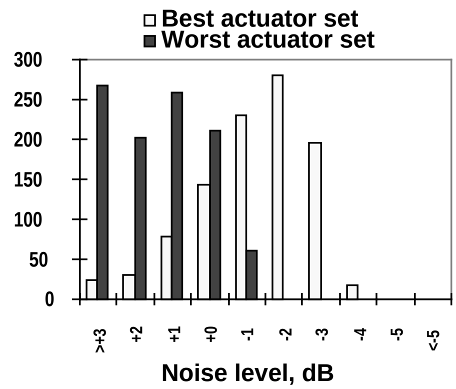


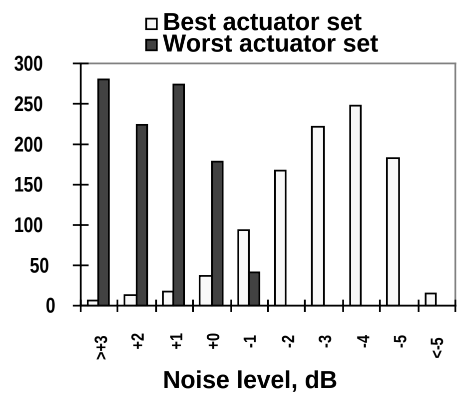
Figure 5. Schematic of composite cylinder layout.



(a) 210 Hz.



(b) 230 Hz.



(c) 275 Hz.

Figure 6. Histograms of noise reduction potential for four best and four worst actuators, with randomly selected sensor locations.

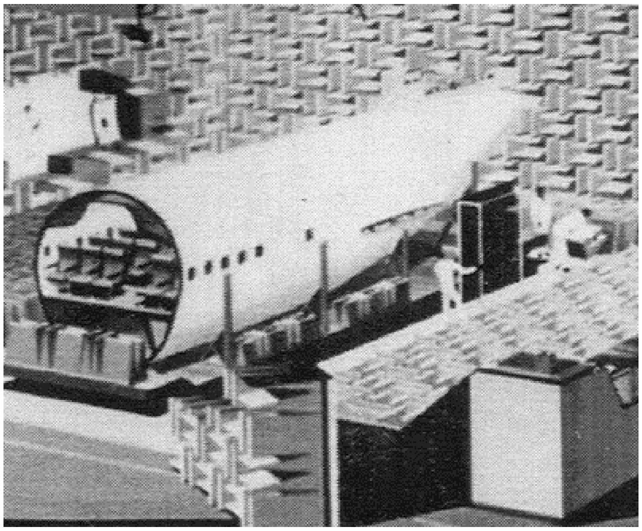
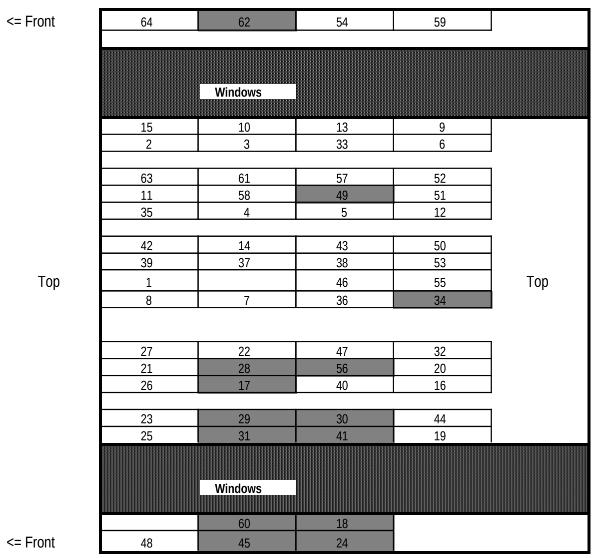
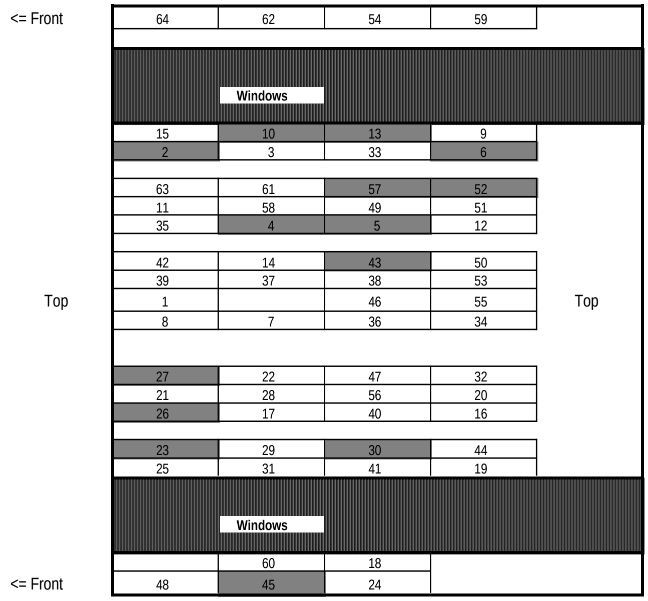


Figure 7. Fuselage Acoustic Research Facility.



(a) Constrained.

Figure 8. Best actuator locations selected, with constrained or unconstrained optimization procedure.



(b) Unconstrained.

Figure 8. Concluded.

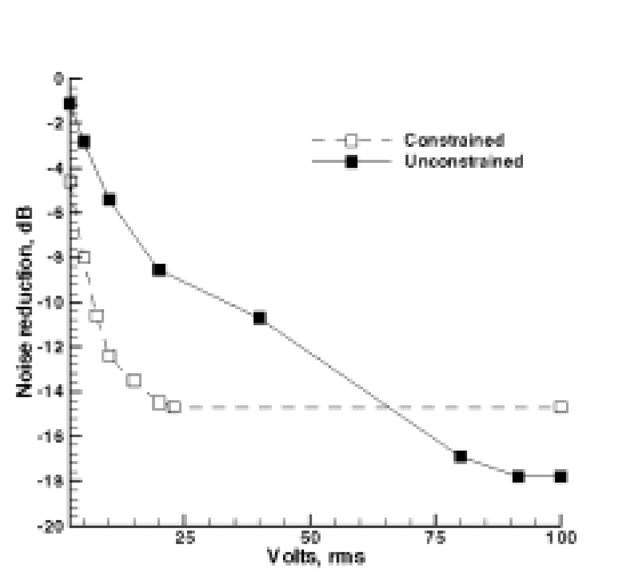


Figure 9. Noise reduction potential for sets of 14 actuators selected with and without constraints on maximum voltage input.